First Measurement of Uranium/Thorium ratio in a very old star: Implications for the Age of the Galaxy

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Abstract. During an ESO-VLT large programme devoted to high resolution spectroscopy of extremely metal-poor stars selected from the HK survey of Beers and colleagues, the [Fe/H] = −2.9 giant CS 31082-001 was found to be as enriched in neutron-capture r-process elements as CS 22892-052, but with a much-reduced masking by molecular lines. This allowed the detection and measurement of the uranium line at 3859 Å for the first time in an extremely old star. By making use of the relatively short ^{238}U decay (half-life 4.47 Gyr) we obtain a radioactive dating of the formation of the r-process elements in this star, born in the early days of the Galaxy.

1. Introduction

Radioactive decay provides a very direct and accurate measurement of time between the epoch of formation and the present, if one also has a means of estimating the abundance ratio of the radioactive element relative to a stable

element (or to another radioactive element having a substantially different half-life). So far only the ratio of the abundance of ^{232}Th to a stable element, usually Eu (also primarily produced by the rapid neutron capture process), has been used as cosmo-chronometer. We report here the measurement of the abundance of ^{238}U, which has the great advantage of having a smaller half-life than ^{232}Th (4.47 Gyr instead of 14.05 Gyr). This measurement was made in CS 31082-001, an extremely metal-poor star ([Fe/H] $= -2.9$) selected from the HK survey of Beers and collaborators (see Beers 1999 for a summary). This star is more metal-deficient than the globular clusters, and was likely born in the very early Galaxy. This measurement, reported in a letter to Nature (Cayrel et al. 2001, issue of February 8, 2001), was made with the ESO/VLT unit 2 (Kuyen) telescope, and the UVES spectrograph. In this presentation I shall concentrate on a discussion of the abundances of U and Th in CS 31082-001, and the consequences for radioactive dating of the material in this star. In a contribution by Hill et al. (this volume) the abundances of the other neutron-capture elements in CS 31082-001 are discussed. In another contribution Toenjes et al. (this volume) present computations of the expected production ratios of U/Th, U/Eu, U/Ir, Th/Eu, and others. Christlieb et al. (this volume) discuss a strategy for future detection of additional r-process enhanced metal-poor stars that might be used as cosmo-chronometers (see also the discussion by Sneden et al., this volume).

2. The Spectroscopic Observation OF CS 31082-001 and Comparison with CS 22892-052

High-resolution VLT/UVES spectra, in the region of the U II line at 3859.57 Å, are shown in figures 1 and 2, respectively, for the star CS 22892-052, already known to be greatly enriched in r-process neutron-capture elements (Sneden et al. 1996), and the newly discovered star CS 31082-001.

It is quite clear from these spectra, that both stars are considerably enriched in r-process elements – the primary difference between the two stars is the much reduced contamination of atomic lines by molecular features (mainly CH and CN) in CS 31082-001. The visibility of the U II line, excellent in CS 31082-001, is spoiled in CS 22892-052 by the presence of the CN line at 3859.67 Å . The alreday high signal-to-noise ratios of these spectra are shown here in fig. 1 and 2, enhanced by a convolution with a Gaussian kernel having FWHM equal to half the resolution of the spectrograph (only one quarter of the FWHM of the stellar lines – producing a negligible loss in spectral resolution). In the spectrum of CS 22892-052 the U II line is at the limit of the noise for two reason: it is blended with the stronger CN line and the line is intrinsically weaker than in CS 31082-001. Only upper limits to uranium abundance have been given so far in CS 22892-052.

Another considerable advantage of the lower blending by molecular lines in CS 31082-001 is that we have identified 14 individual lines of thorium in its spectrum, 10 of which are sufficiently unblended to allow for a precise determination of its abundance. In CS 22892-052 there are thus far only 3 lines that might be used for this abundance measurement (Sneden & Cowan 2000). Figure 3 illustrates this point (to be compared with fig. 2 of Sneden & Cowan 2000).
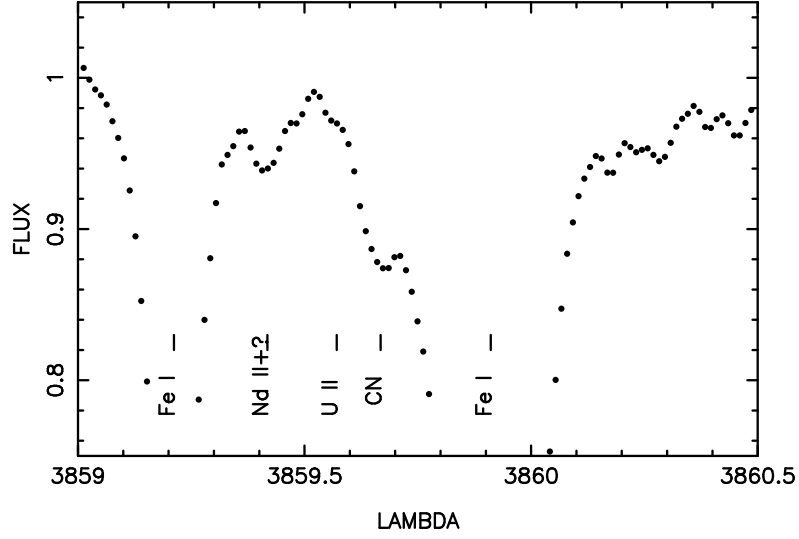
Figure 1. VLT/UVES spectrum of the star CS 22892-052 in the region of the uranium line at 3859 Å
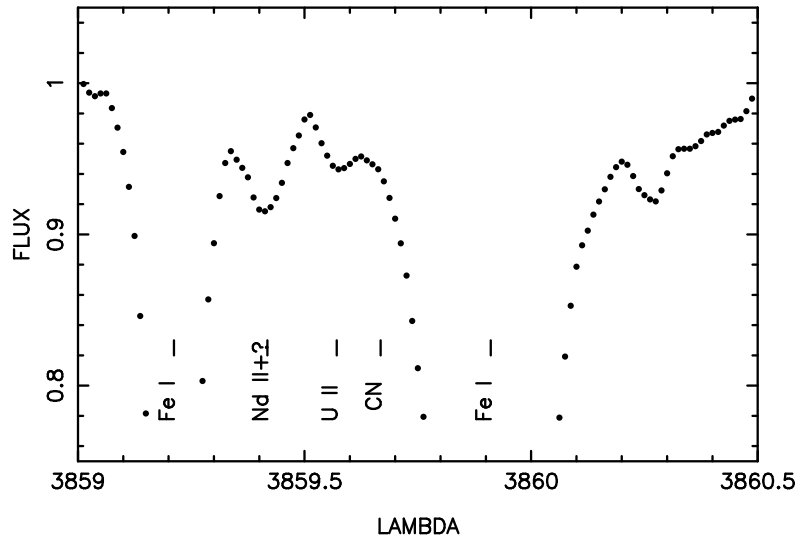

Figure 2. VLT/UVES spectrum of the star CS 31082-001 in the region of the uranium line at 3859 Å
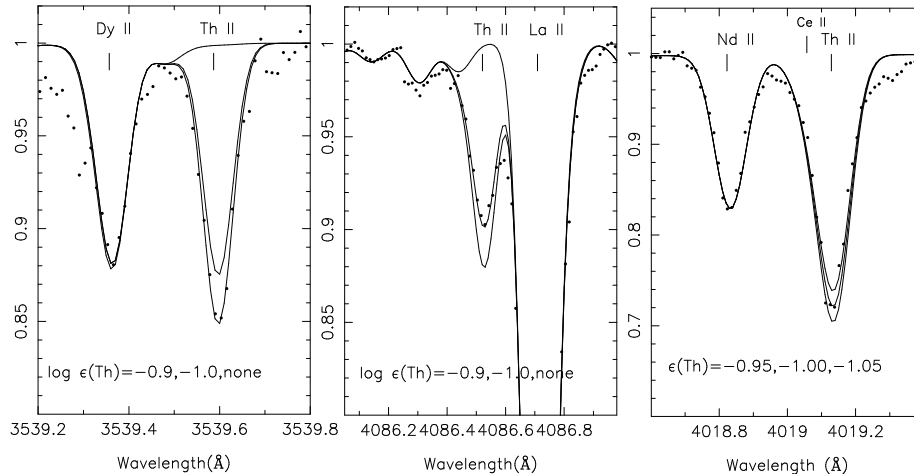
Figure 3.   Synthesis of three thorium lines in CS 31082-0012

3.   The Abundances of U and Th in CS 31082-001, and the Age Determination

It has been claimed by Goriely & Clairbaux (1999) that the ratio U/Th might be a better cosmo-chronometer than either Th/Eu or Th/Dy, because of the much smaller mass difference between Th and U than between either one of these two actinides and the lighter lanthanides (see their fig. 2–5). It is therefore of particular interest to use the ratio U/Th to determine the age of formation of these elements, presumably in a type-II SN explosion, the products of which were later trapped in the atmosphere of stars such as CS 31082-001, and which have both decayed with a constant rate, ever since. Table 1 summarizes the relationship between the logarithmic concentrations of three chronometer pairs and time.

In Table 1, "r" refers to any stable neutron-capture element produced by the r-process, i.e., with a time between two consecutive neutron captures smaller than the spontaneous decay of the target. Because of the large numerical factor 46.7 in the first expression, resulting from the long half-life of Th, this chronometer is less favourable than the other two. At first view, the second expression is the best choice. However, the warning of Goriely and Clairbaux suggests that it might be quite difficult to reduce the uncertainty on $\log(U/r)_0$, as the first stable r-elements are still far from U and Th in nuclear mass. Therefore, the

Table 1.   Time Δt elapsed during epochs at which two abundance ratios are known, an initial epoch labeled with the subscript "0", and the present epoch labeled with the subscript "obs"

Time elapsed		Expression
Δt	$=$	$46.7[\log(\mathrm{Th/r})_0 - \log(\mathrm{Th/r})_{obs}]$
Δt	$=$	$14.8[\log(\mathrm{U/r})_0 - \log(\mathrm{U/r})_{obs}]$
Δt	$=$	$21.8[\log(\mathrm{U/Th})_0 - \log(\mathrm{U/Th}_{obs}]$

last expression is probably the safest choice. The increase in the multiplicative coefficient with respect to the second expression is likely to be more than compensated for by the reduction in the uncertainty of the production ratio of $\log(\mathrm{U/Th})_0$.

For the present, the best we can do is to select estimates of the $\log(\mathrm{U/Th})_0$ ratio, and derive Δt from expression 3 of Table 1. In Table 2 we also provide, for comparison, the ages derived from expression 2, using the heaviest observable stable elements Os and Ir. The errors do not include the uncertainties on the theoretical ratios, but do include all other known sources of errors, including uncertainties on the oscillator strengths. Assuming a 0.1 dex uncertainty on $\log(\mathrm{U/Th})_0$, and a 0.15 uncertainty on $\log(\mathrm{U/Th})_{obs}$, leads to a global uncertainty of 4 Gyr arising from the use of U/Th ratio alone. However, the two independent ratios U/Os and U/Ir lead to a similar value for the age, with smaller net error bars, because of the smaller multiplicative coefficient, 14.8 instead of 21.8. We thus consider 3 Gyr to be a reasonable estimate of the global error, taking into account the the results of the three chronometer pairs.

Table 2.   Ages of r-process elements in CS 31082-001 and their associated production ratios. The references are (1) Cowan et al. 1999, (2) Goriely & Clairbaux 1999 (3) Toenjes et al. 2001 (this volume)

pair	Log(prod. ratio)	ref	Log(observ. ratio)	Age
U/Th	-0.255	1	-0.74 ± 0.15	10.6 ± 3.3
U/Th	-0.10	2	idem	14.0 ± 3.3
U/Th	-0.16	3	idem	12.6 ± 3.3
U/Os	-1.27	1	-2.19 ± 0.18	13.6 ± 2.7
U/Ir	-1.30	1	-2.07 ± 0.17	11.4 ± 2.5

4. Relationship Between the Value of $(U/Th)_0$ and the measured ratio in CS 310822-001 Versus the Solar (U/Th) values

The present solar value of $\log(U/Th)$ is -0.59±0.05, according to Grevesse and Sauval (1998). The value in CS 31082-001 is -0.74±0.15 (Table 1). The values at the birth of the Sun are the preceeding ones corrected by the same factor: the variation of the ratio during 4.6 Gyr, *i.e* 0.211 dex , according to table 1, or respectively -0.379 and -0.259, still differing by 0.15 dex.

If U and Th are always produced in the proportion $(U/Th)_0$, it is indeed expected that the value of $\log(U/Th)$ is smaller in CS 31082-001 than in the Sun, because it has been decaying over the full age of the Galaxy, whereas in the Sun it has been decaying over any time between 4.6 Gyr and the age of the Galaxy, depending on its epoch of formation and injection into the pre-solar nebula. If we assume that U and Th are formed together continuously during the time preceeding the birth of the Sun, it is possible to derive expressions for the build-up of the concentrations ϵ_U and ϵ_{Th} of U and Th in the interstellar medium as:

$$d\epsilon_U = a_U f(t)dt$$

$$d\epsilon_{Th} = a_{Th}f(t)dt$$

with:

$$\frac{a_U}{a_{Th}} = (U/Th)_0$$

where $f(t)$ is the common history function of the production of U and Th before the birth of the Sun. After the birth of the Sun, U/Th has evolved identically in the Sun and in CS 31082-001, so the difference between the ratios is only due to the fact that the decay between the origin of the Galaxy and the time of birth of the Sun $t_\odot$ is for CS 31082-001:

$$\frac{\epsilon_U(CS)}{\epsilon_{Th}(CS)} = (U/Th)_0 \exp(-(\alpha_U - \alpha_{Th})t_\odot \tag{1}$$

where $\alpha_U = 0.1551$ and $\alpha_{Th} = 0.04933$.

For the Sun at the same time $t_\odot$:

$$\epsilon_U(\odot) = \int_0^{t_\odot} a_U f(t)exp(-\alpha_U(t_\odot - t))dt$$

$$\epsilon_{Th}(\odot) = \int_0^{t_\odot} a_{Th}f(t)exp(-\alpha_{Th}(t_\odot - t))dt$$

leading to:

$$\frac{\epsilon_U(\odot)}{\epsilon_{Th}(\odot)} = (U/Th)_0 \frac{\int_0^{t_\odot} f(t)exp(-\alpha_U(t_\odot - t)dt}{\int_0^{t_\odot} f(t)exp(-\alpha_{Th}(t_\odot - t)dt} \tag{2}$$

If $f(t)$ or $f(t/t_\odot)$ is known, the equations (1) and (2) contain only two unknown quantities, $(U/Th)_0$ and $t_\odot$. It is then possible to derive $(U/Th)_0$ and $t_\odot$, without knowing $(U/Th)_0$ a-priori. Actually, this is not our goal, as we prefer

to obtain $(U/Th)_0$ from physicists, and thereby derive as much information on the astrophysical unknowns as possible, rather than derive nuclear properties from astrophysical data. But at least we can see what a particular value of $(U/Th)_0$ implies for the history function of production of the r-process elements in the solar system. Assuming a uniform production rate, the result is easily derived. Taking the ratio of eqn(2) over eqn(1) yields:

$$\frac{\epsilon_U(\odot)/\epsilon_{Th}(\odot)}{\epsilon_U(CS)/\epsilon_{Th}(CS)} = \frac{\int_0^{t_\odot} exp(\alpha_U t)dt}{\int_0^{t_\odot} exp(\alpha_{Th}t)dt} \tag{3}$$

The integration is straightforward, and the value of $t_\odot$ which gives the observed ratio of 1.41 (the antilog of 0.15) is 5.9 Gyr. Adding this to the 4.6 Gyr elapsed since the birth of the Sun gives an age for CS 31082-001 of 10.5 Gyr. Plugging the value of $t_\odot$ value in eqn(1) gives $(U/Th)_0$=-0.258, a value almost equal to that listed on the first line of Table (1). It is equally easy to find the result for $f(t) = exp(-\lambda t)$. The value of the parameter λ leading to the value of $(U/Th)_0$=-0.16 in the second line of Table 1 is 0.25, giving $t_\odot = 8$ Gyr, or as listed in Table 1, a total age of 12.6 Gyr. This implies a decay of the production rate of about a factor 7 between the epoch of the early Galaxy and the epoch of the birth of the Sun. This simple calculation emphasizes the astrophysical impact of the exact value of $(U/Th)_0$.

5. Conclusion

Uranium has been detected, and had its abundance measured, in a very metal-poor star that was born in the early Galaxy, likely before the formation of the globular clusters. It has been possible, for the first time, to use the ratio U/Th for determining the age of formation of these elements in the early Galaxy. The accuracy of the result, 12.6 ± 3 Gyr, is still rather severely limited by the 0.15 dex uncertainty on the abundance ratio derived from observation, and by the 0.1 uncertainty on the theoretical estimation of the U/Th production ratio. Progress can be expected in the near future in three areas: (i) Improvement in the measurement of the oscillator strengths of U and Th (ii) Improvement in the estimation of the production ratio U/Th$_0$, based on measurement of the abundances of other heavy elements in CS 31082-001 such as Pb, Bi, Os, Pt, and Ir, as well as refinements in the nuclear physics models, and (iii) Discovery of other metal-deficient r-process enhanced stars in which U and Th can be measured, to improve the statistics and to provide a valuable check of the stability of the production ratio in several stars.

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